New limit on $0\nu\beta\beta$ decay of ^{100}Mo with the CUPID-Mo experiment

Dounia Helis on behalf of the CUPID-Mo collaboration

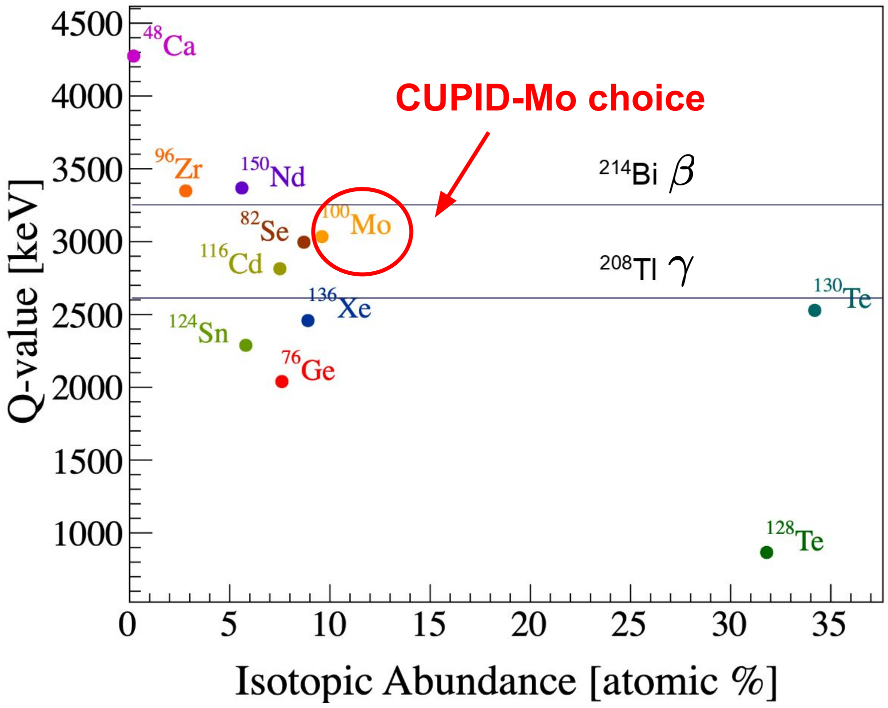
Double-Beta Research in France Workshop II

16/10/2020

Outline

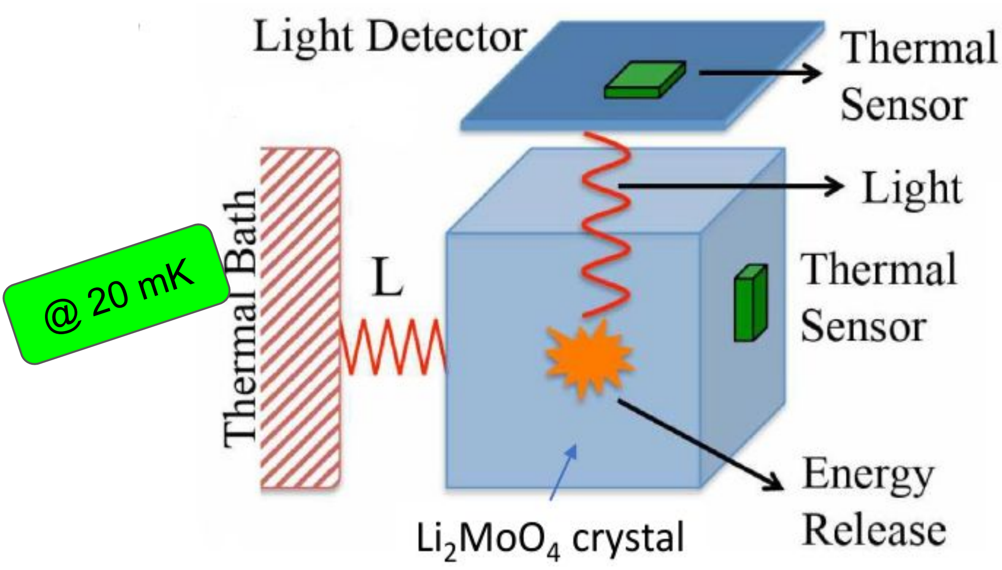
- $0\nu\beta\beta$ decay of ^{100}Mo in Li_2MoO_4 crystals
- Scintillating bolometers
- From LUMINEU to CUPID-Mo
- The CUPID-Mo detector array
- CUPID-Mo detector performances
- Analysis chain
- Search for $0\nu\beta\beta$ decay of ^{100}Mo

Why ^{100}Mo ?

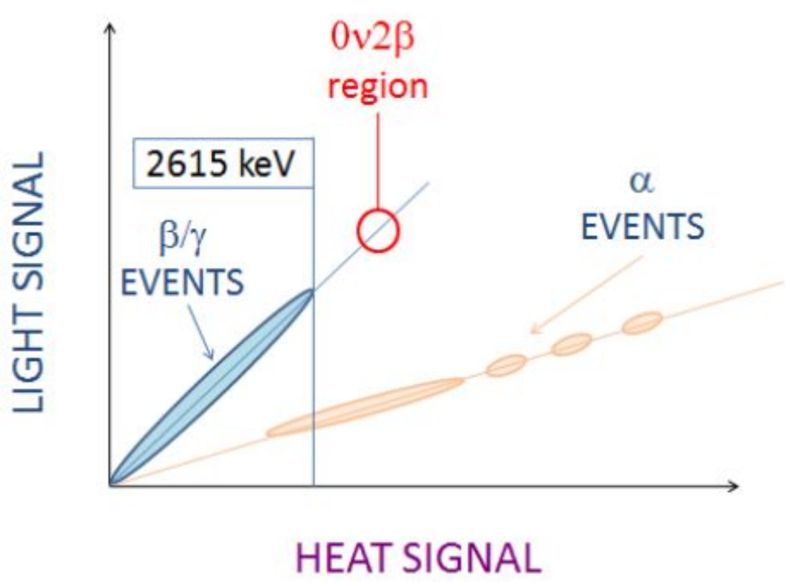


- ★ $^{100}Mo \longrightarrow ^{100}Ru + 2e^-$
- ★ **$Q_{\beta\beta}$ = 3034 keV**
- ★ I.A. = 9.7%
- ★ Enrichable by gas centrifugation
- ★ Can be embedded in scintillating crystals ⇨ **Li_2MoO_4 crystals**

Scintillating bolometers



- Bolometer = high energy resolution
- Double readout ⟹ particle ID and full α/β(γ) separation
- Source=detector ⟹ high efficiency



CUPID-Mo thermal sensor: **Neutron Transmutation Doped Ge (NTD-Ge)**

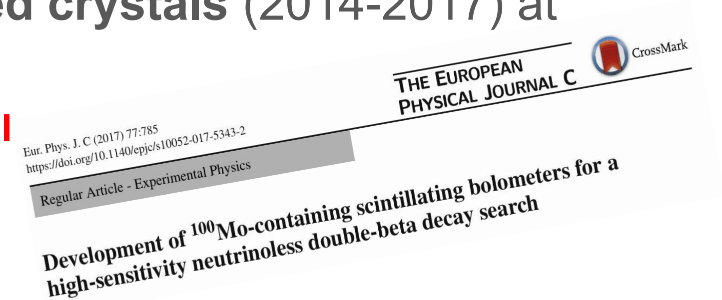
From LUMINEU to CUPID-Mo

- The technology based on scintillating bolometers with **$Li_2{}^{100}MoO_4$** crystals was successfully developed by LUMINEU
- **Multiple** tests were done with **natural and enriched crystals** (2014-2017) at **LSM** and LNGS leading to important results:
  - High-purity crystals → **negligible loss of enriched material**
  - Reproducibility → excellent performance uniformity
  - Energy resolution → **4-6 keV FWHM in ROI**
  - α/β separation power → **> 99.9 %**
  - Internal radiopurity → **< 5 μBq/kg in ^{232}Th, ^{226}Ra; < 5 mBq/kg in ^{40}K**

Compatible with

b ≲ 10^{-4} [counts/(keV kg y)]

NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)
AIP Conf. 1894, 020017 (2017)


Eur. Phys. J. C (2017) 77:785
https://doi.org/10.1140/epjc/s10052-017-5343-2

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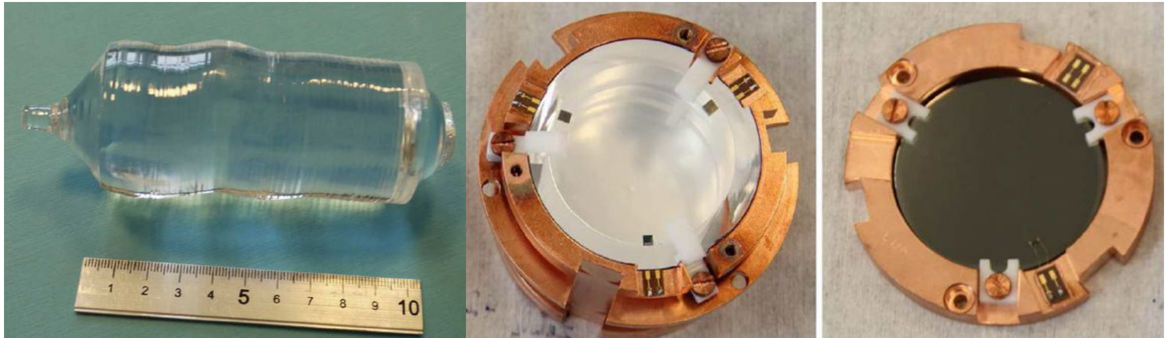
Regular Article - Experimental Physics

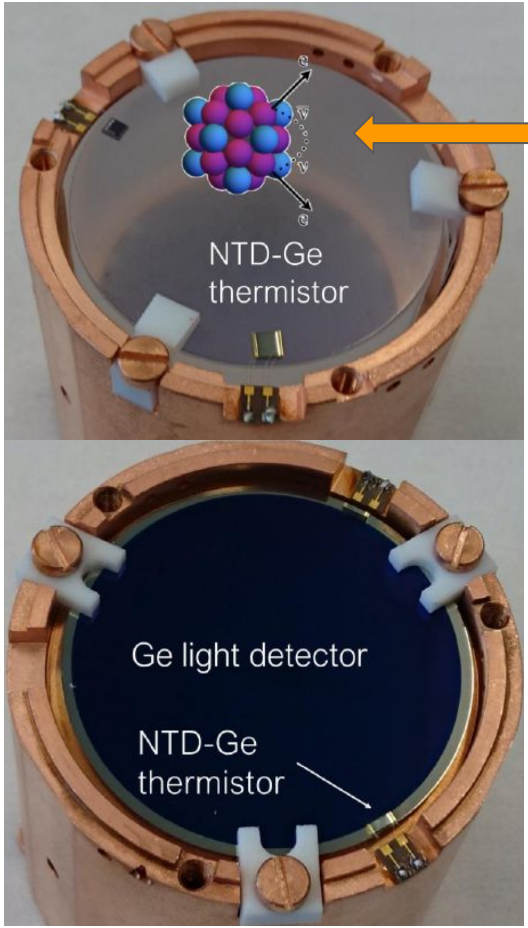
Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search



CUPID-Mo detectors

Single module

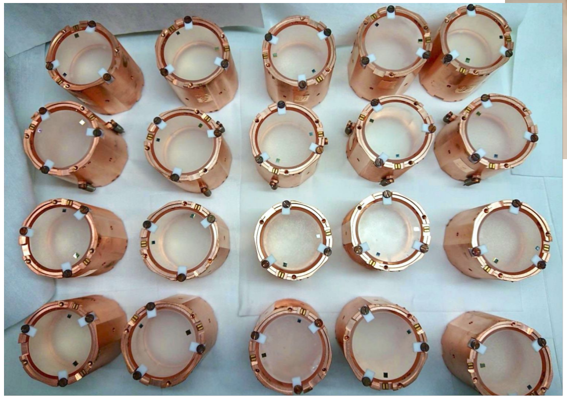
Copper = thermal bath

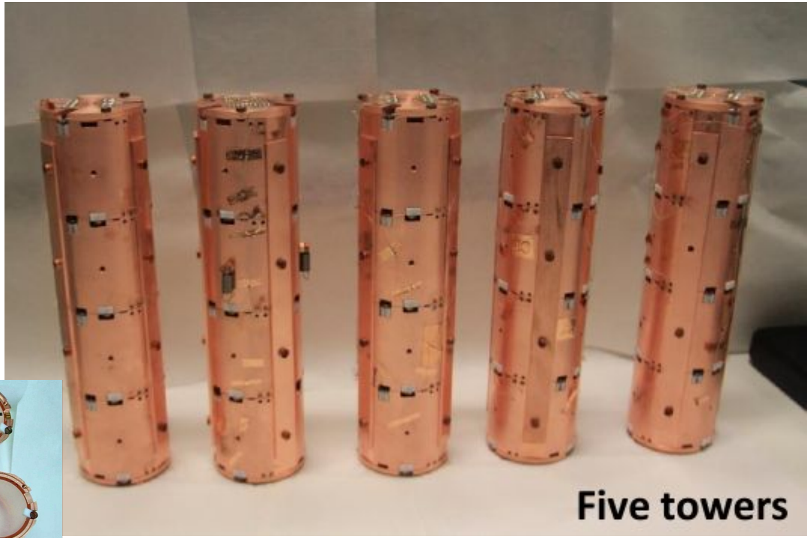


Teflon = weak thermal link

Source ^{100}Mo = Detector $Li_2{}^{100}MoO_4$
High efficiency

× 20



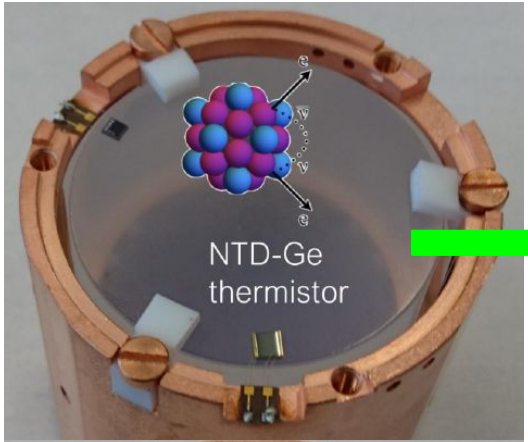


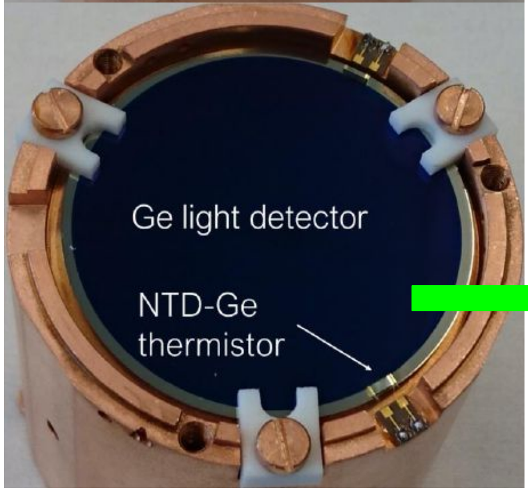
20 x $Li_2{}^{100}MoO_4$ (D44*45 mm, ~0.21 kg)

- **Enrichment 96.6 ±0.2 %**
- **4.158 kg $Li_2{}^{100}MoO_4$**
- **2.264 kg ^{100}Mo**

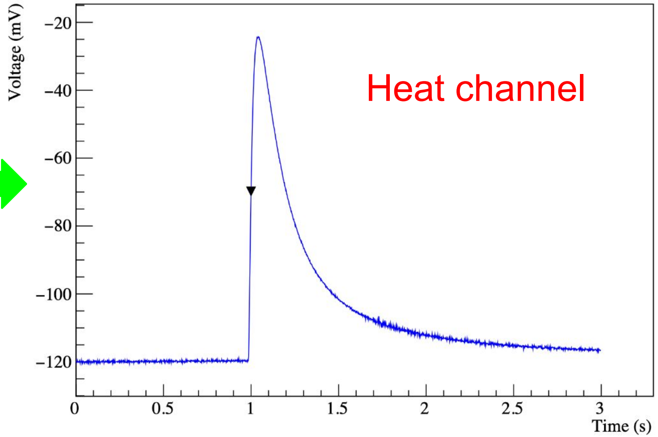
CUPID-Mo detector response

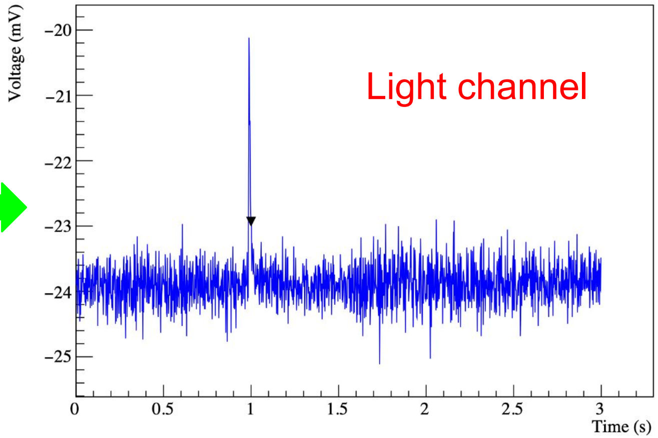
Copper = thermal bath



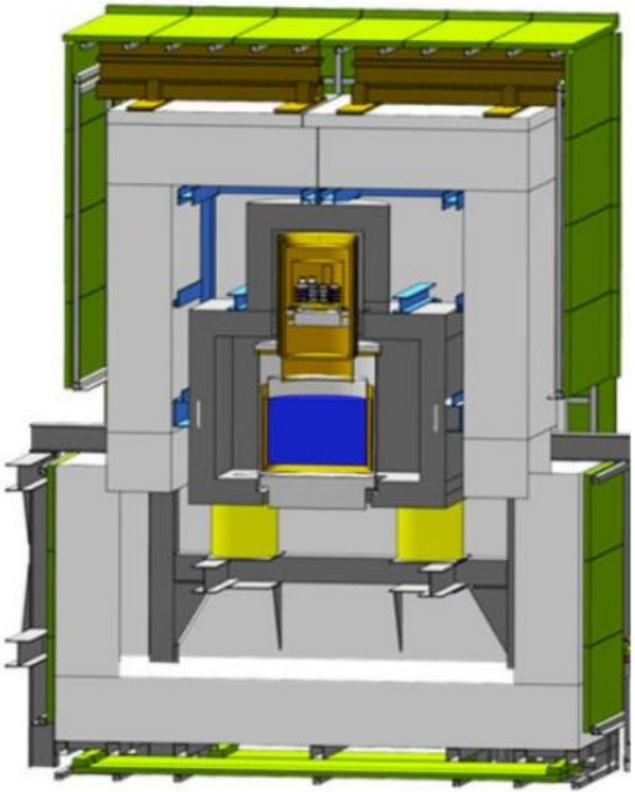


Teflon = weak thermal link

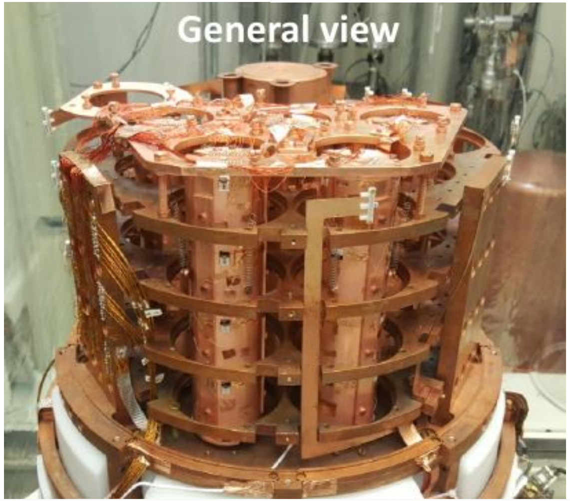


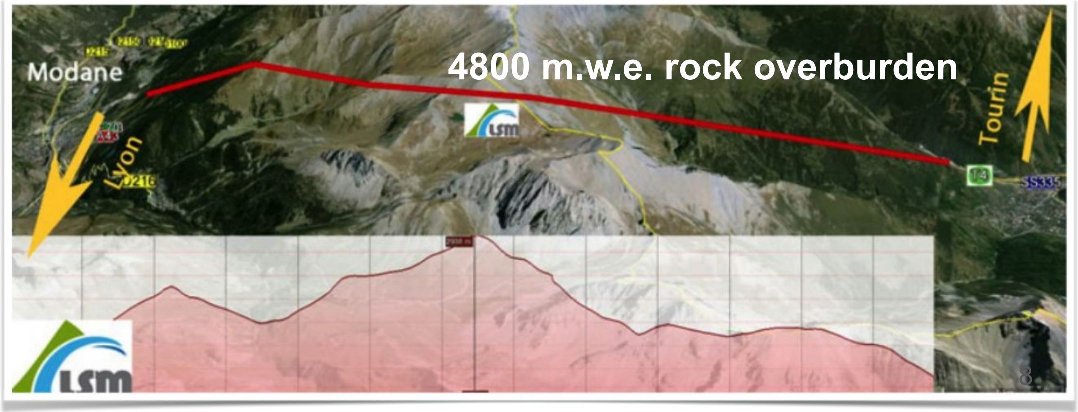


The CUPID-Mo experiment at Modane

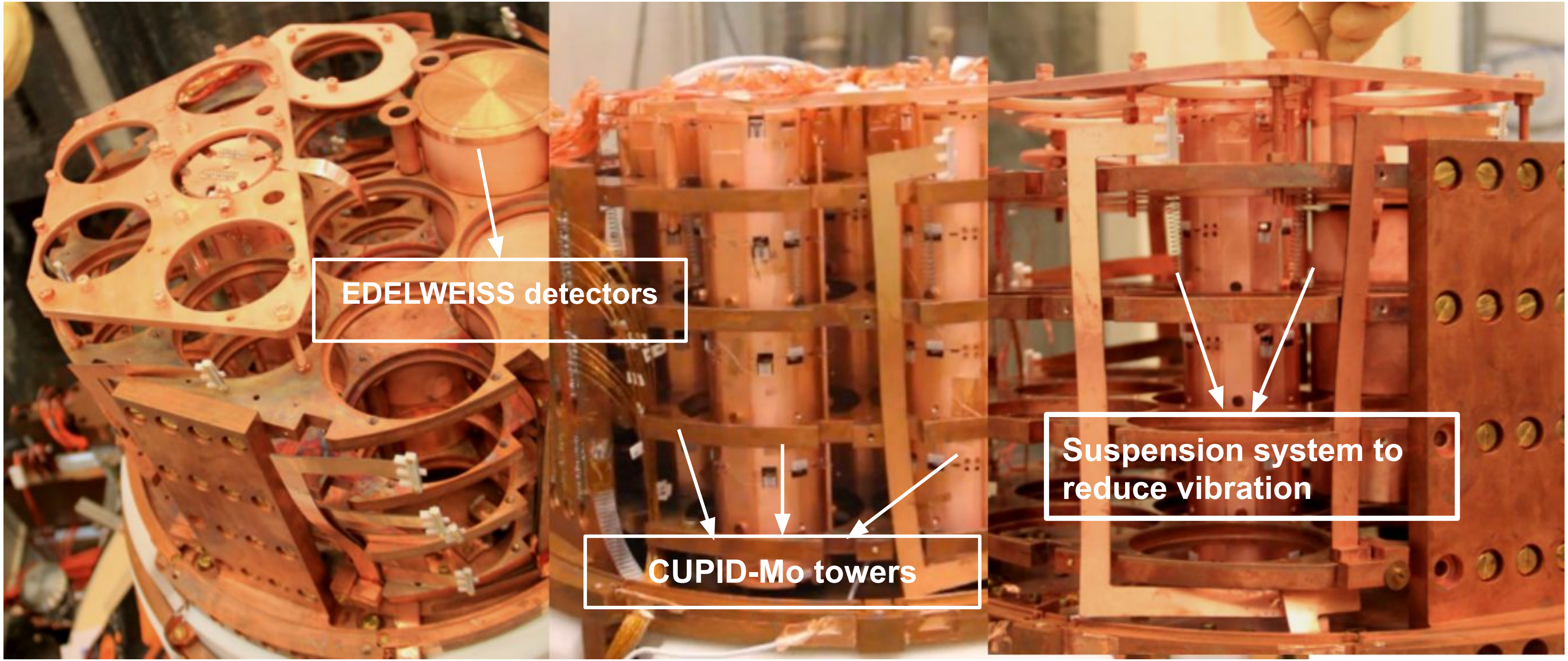


- Shared cryogenic EDELWEISS set-up
- The detectors were operated at 20-22 mK
- Physics data taking from March 2019 to July 2020

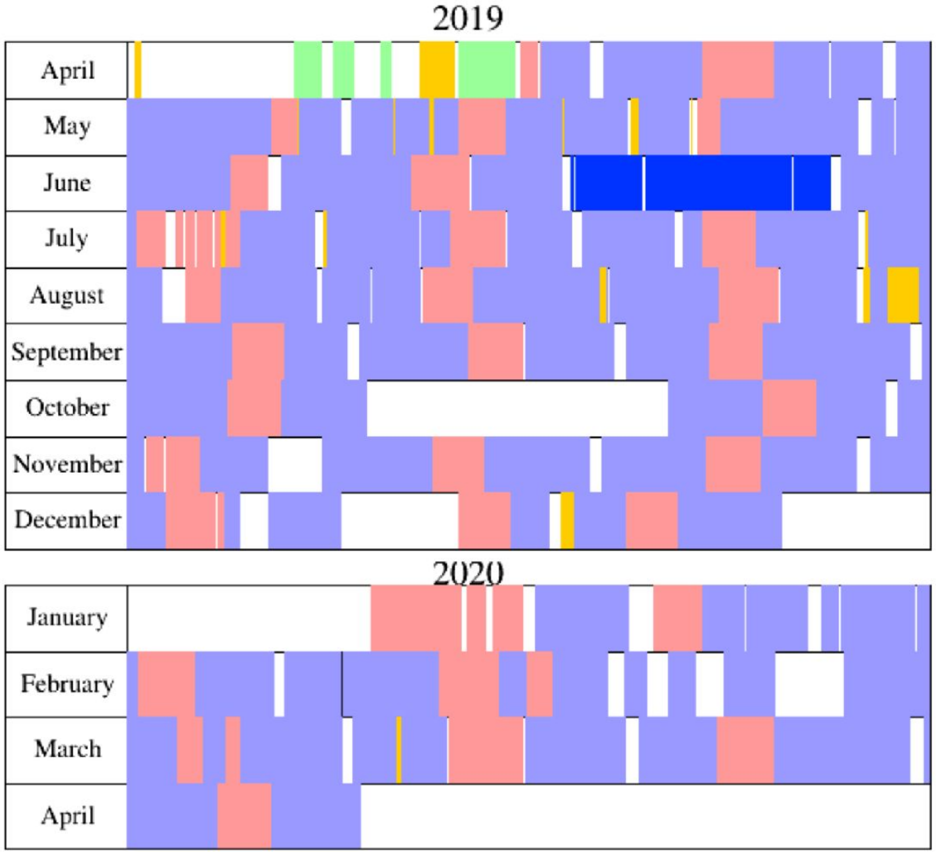


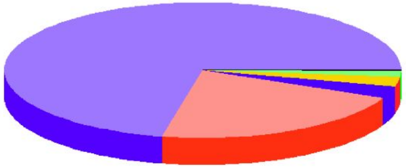


The CUPID-Mo experiment at Modane



CUPID-Mo data taking
Neutrino 2020 data





March 2019 - April 2020 (380 days)
- **7 long datasets**, 1-2 month scale
- 3 short datasets (single calibration periods)

Not used in the Neutrino 2020 analysis - extra work needed on energy-scale uncertainty
- Rejection of periods of temperature instabilities

Selected data for Neutrino 2020

➔ 200 days of physics data (94%)

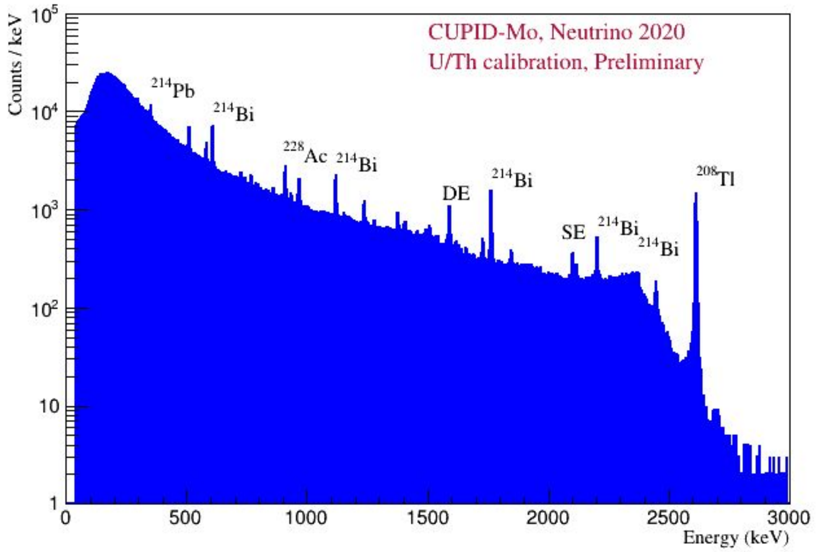
➔ 59 days of calibration data (88%)

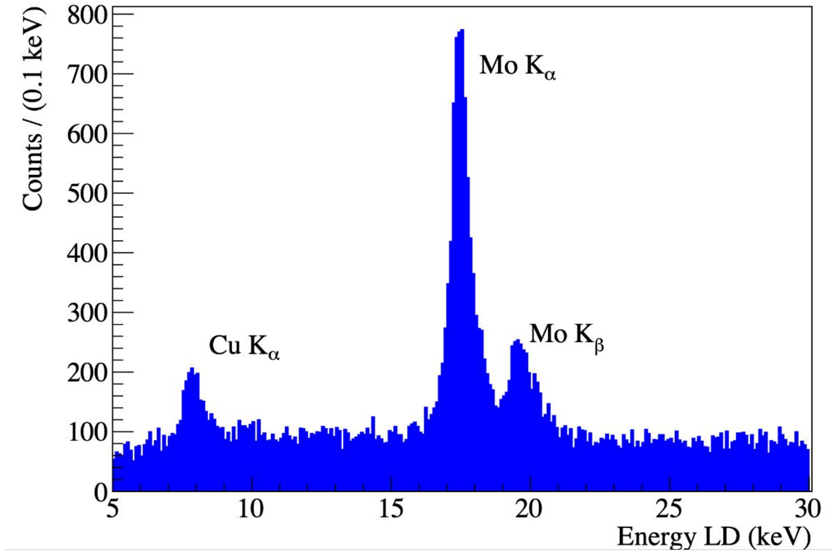
2.17 kg.yr of physics data

CUPID-Mo calibration

- LMO detectors have relatively low mass ~210 g and low density 3.07 g/cm^3
- Time dedicated to calibration ~ 23% of data taking
- U/Th source

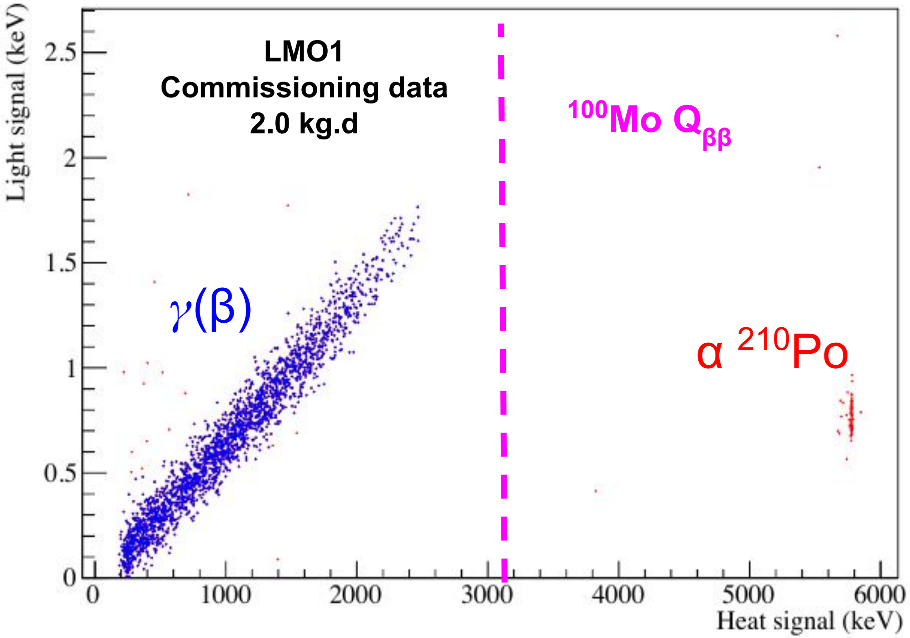
- Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search => Impossible to use low energy source for LD calibration
- Use the Mo X-ray escape peak from high intensity irradiation of the crystals (^{60}Co)





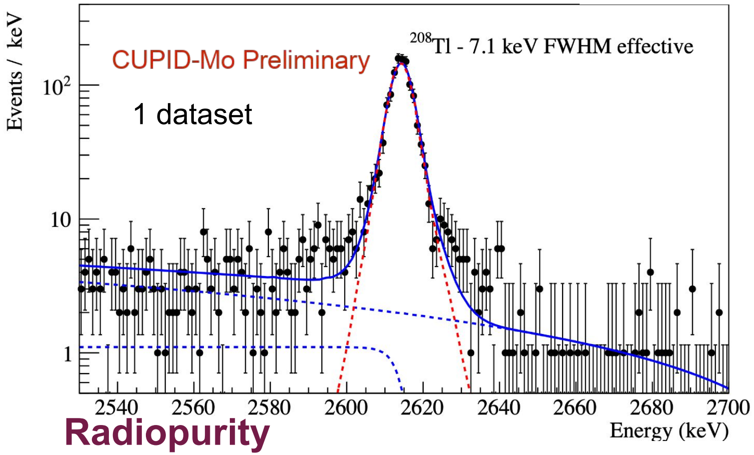
CUPID-Mo performances

Light yield



- Typical $\gamma(\beta)$ LY: 0.6-0.7 keV/MeV
- Quenching factor of α: 20%
- > 99.9 % of $\gamma(\beta)/\alpha$ separation

Energy resolution

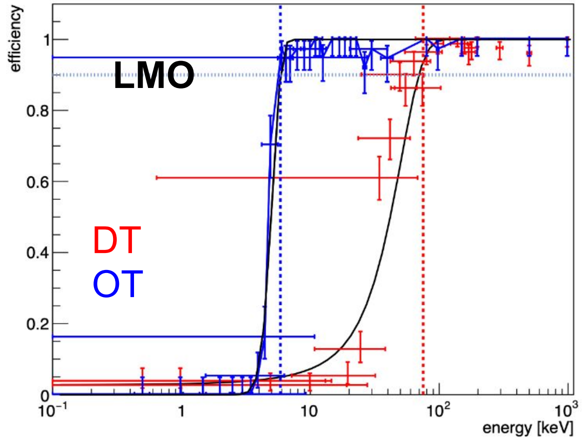


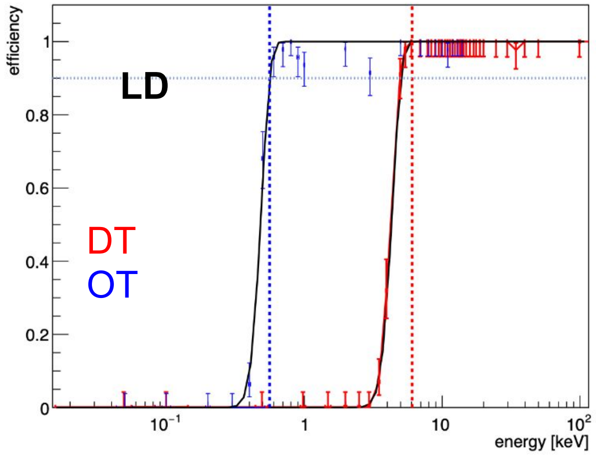
Radiopurity

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	0.22(9)
	^{228}Th	0.38(9)
	^{224}Ra	0.34(9)
	^{212}Bi	0.22(7)
^{238}U	^{238}U	0.35(10)
	^{234}U+^{226}Ra	1.22(17)
	^{230}Th	0.48(12)
	^{222}Rn	0.47(10)
	^{218}Po	0.35(9)
	^{210}Po	95(6)
	^{190}Pt	0.19(8)

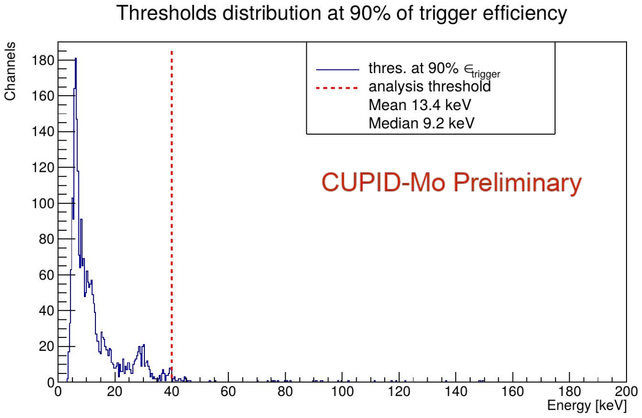
Crystals bulk α activity
19/20 Li_2MoO_4 2.17 kg.yr

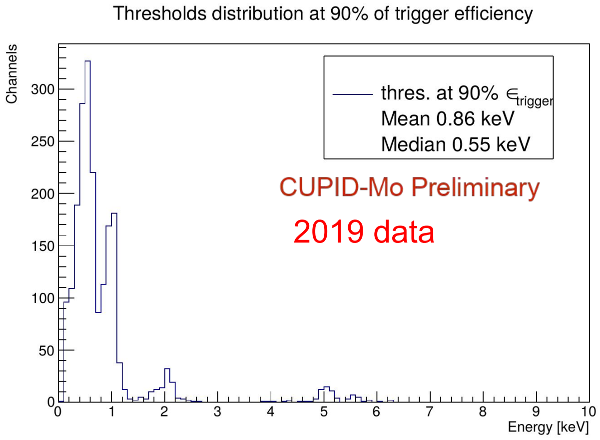
CUPID-Mo performances
Trigger efficiency





- Use of Optimum triggering allows better discrimination between single events and multi-crystal events
- Conservative threshold set to 10 sigma of the baseline rms
- Energy threshold evaluation at 90% of trigger efficiency:
  - inject synthetic events built on the avg. pulse into noise
  - typical LMO threshold ~ 9 keV
  - typical LD threshold ~ 0.5 keV
- Lower threshold can be obtained for low energy analysis such as dark matter searches





Analysis chain and quality cuts

CUORE based data production chain at NERSC

Total efficiency (exposure weighted avg.) $\Rightarrow$ $\epsilon = (90.5 \pm 0.4\ (\text{stat.})\ ^{+0.9}_{-0.2}\ (\text{syst.}))\ \%$

Trigger efficiency

Base cuts

Single trigger
BaselineSlope

Multiplicity

Pulser rejection
M1 - single crystal

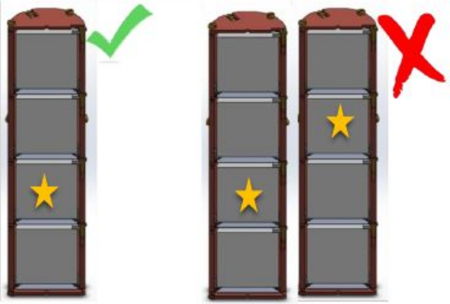
Pulse Shape analysis

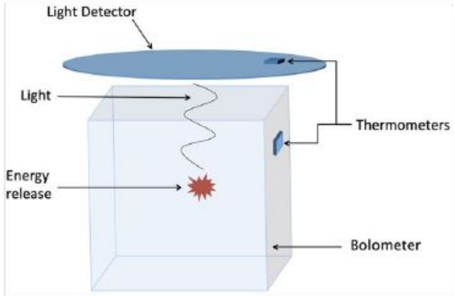
Principal component analysis (PCA)

Light Yield

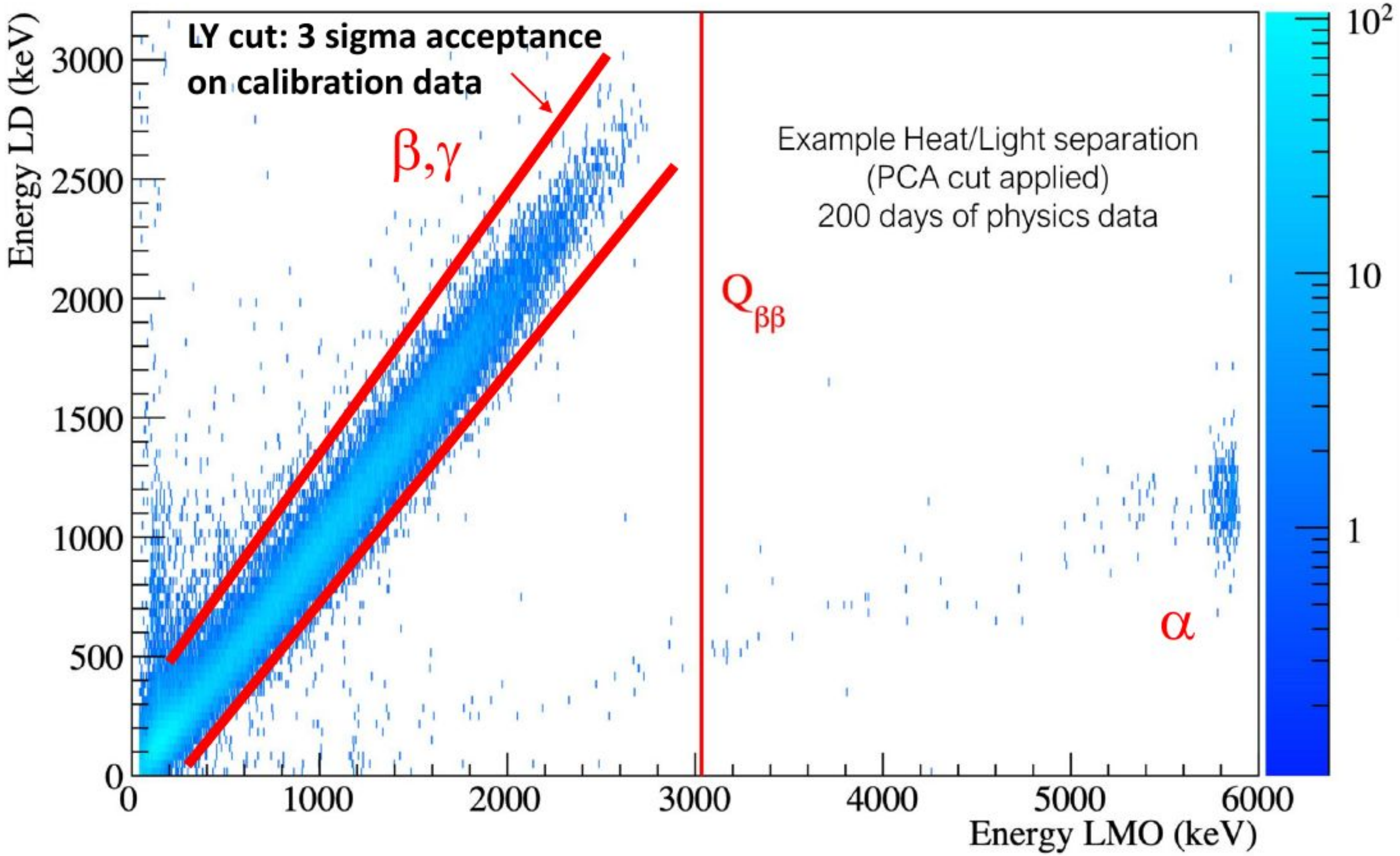
Sum of LD
Consistency of LD

Muon veto anti-coincidence

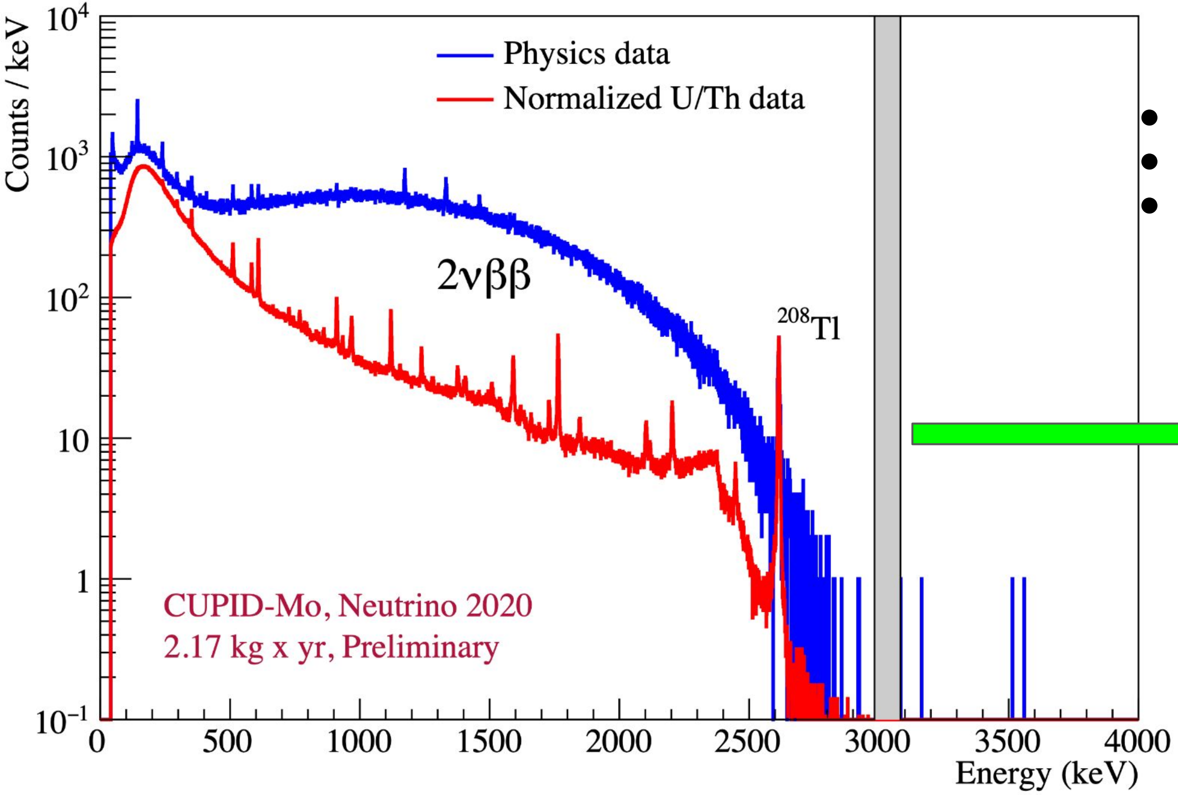




Light yield cut



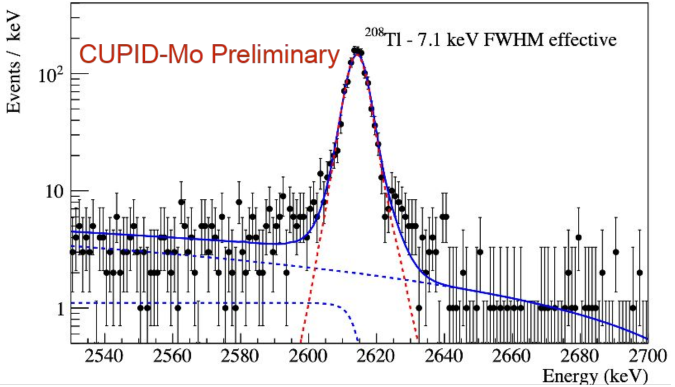
CUPID-Mo blinded data

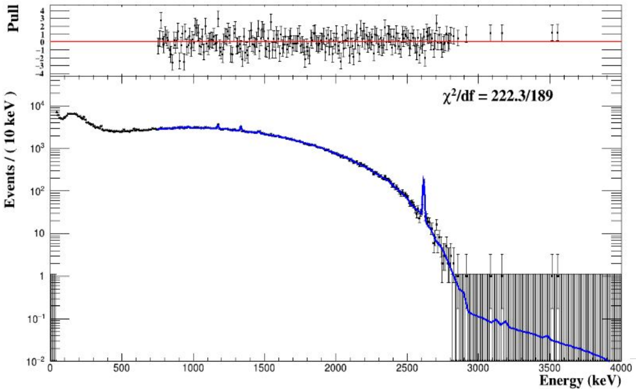


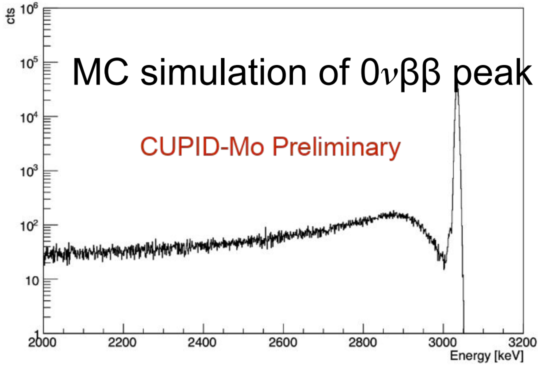
- 200 days of physics data
- 19/20 detectors
- ~7 keV FWHM @ 2615 keV (calibration)

Blinded region
=
100 keV centred around $Q_{\beta\beta}$

How did we define our ROI?

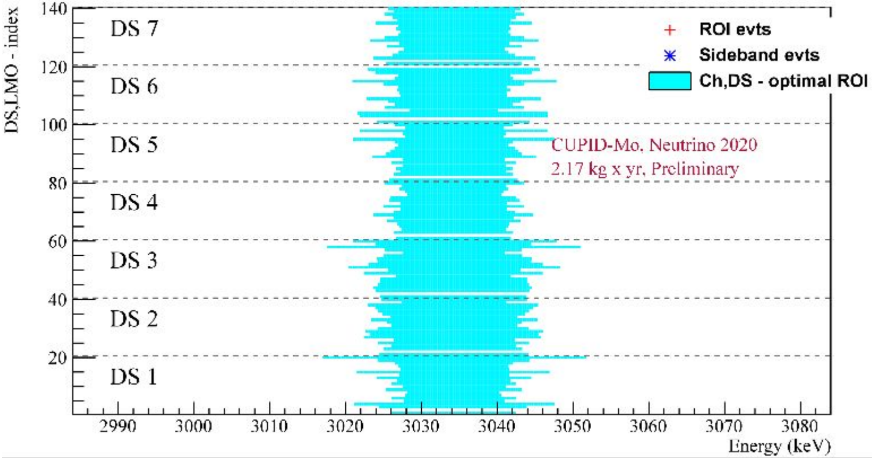




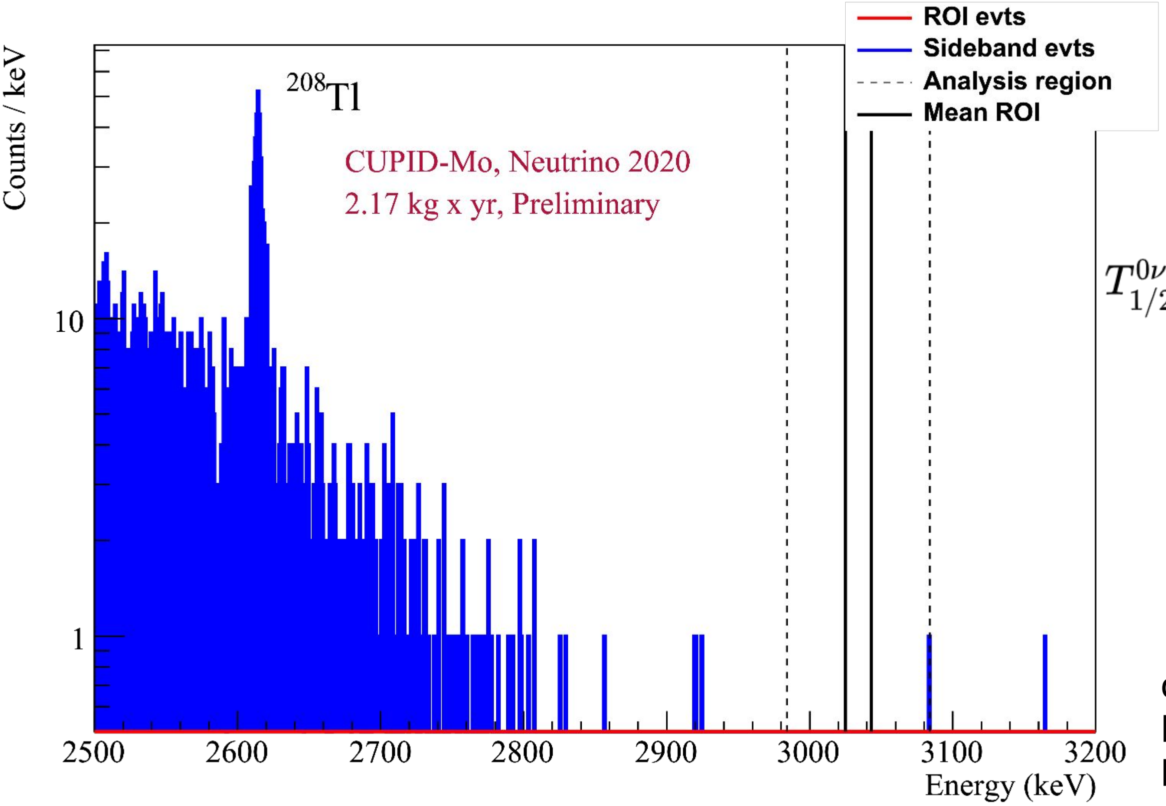


Detector resolution + **Background index** + **0$\nu\beta\beta$ containment Bremsstrahlung escape**

= **ROI**



The new 0νββ decay CUPID-Mo limit



New world leading limit

$$T^{0\nu}_{1/2} > 1.4 \times 10^{24} yr,\ 90\%\ C.I.\ (stat. + syst.)$$

Effective Majorana mass

$$m_{\beta\beta} < (0.31 - 0.54)\ eV$$

considering g_A= 1.27 and dependent on the Nuclear Matrix Element in the light Majorana neutrino exchange interpretation

Conclusions and outlook

- The CUPID-Mo demonstrator based on LUMINEU results took data successfully from March 2019 to July 2020 at LSM
- 19/20 scintillating bolometers showed excellent performances with a good energy resolution (~7 keV at 2615 keV), a PID capability (> 99.9 %) and high radiopurity
- CUPID-Mo set a new world leading limit on the $0\nu\beta\beta$ decay of ^{100}Mo
- A paper to be submitted to PRL is currently under collaboration review
- A paper about our pulse shape analysis is available on arXiv:2010.04033
- The LUMINEU/CUPID-Mo technology is the baseline for the future ton-scale experiment **CUPID** at LNGS
- The analysis of the full data is ongoing (e.g. ^{56}Co calibration, background model, $0\nu\beta\beta$, $2\nu\beta\beta$, $2\beta\beta$ to excited states, DM search,..)

Posters at Neutrino 2020

CUPID-Mo $0\nu\beta\beta$ analysis
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-419.pdf

CUPID-Mo performance
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-404.pdf

CUPID-Mo ^{56}Co calibration campaign
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-374.pdf

CUPID-Mo background model
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-418.pdf

CUPID-Mo low energy analysis prospects
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-448.pdf

CUPID-Mo sensitivity for $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-382.pdf

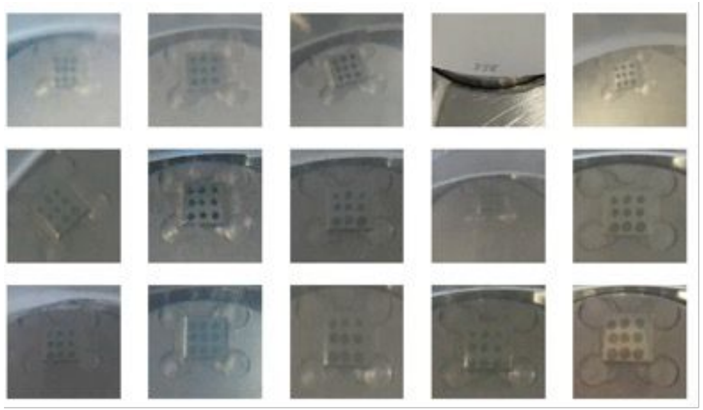
$2\nu\beta\beta$ analysis with CUPID-Mo technology
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-525.pdf

The CUPID-Mo collaboration

Backup slides

Detector assembly chain

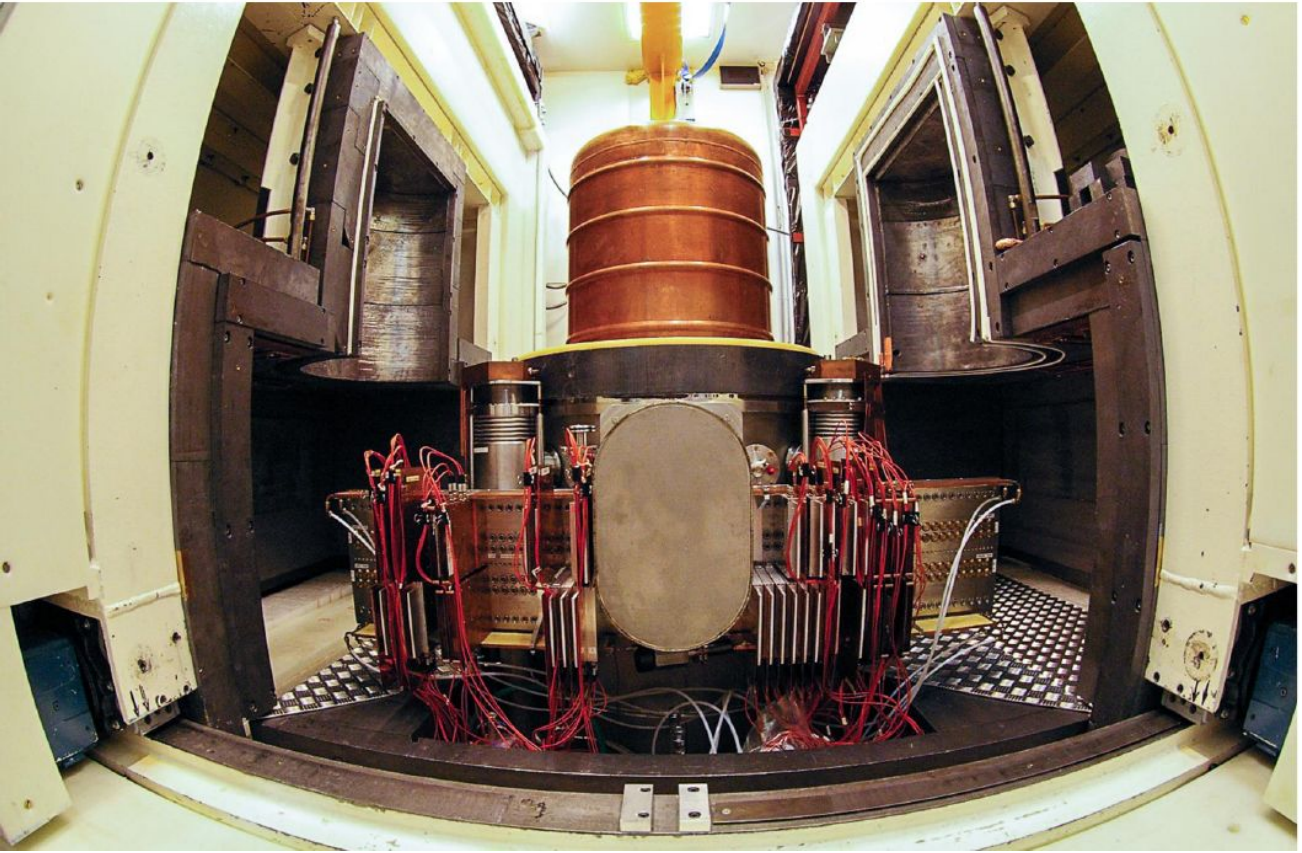
Gluing



Bonding and assembly

at IJCLab (ex CSNSM and ex LAL)

EDELWEISS/CUPID-Mo cryogenic facility

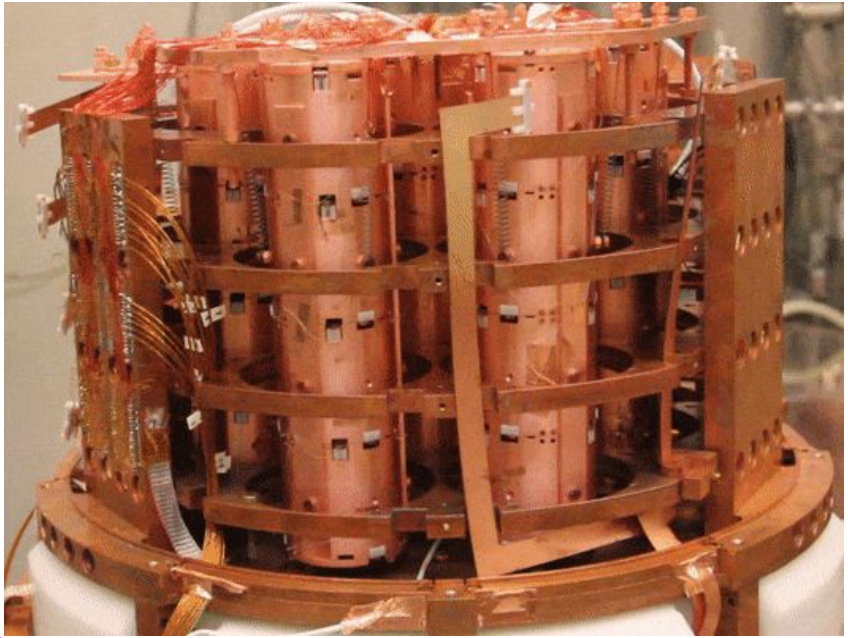


Active and passive shielding designed for the **EDELWEISS dark matter search**

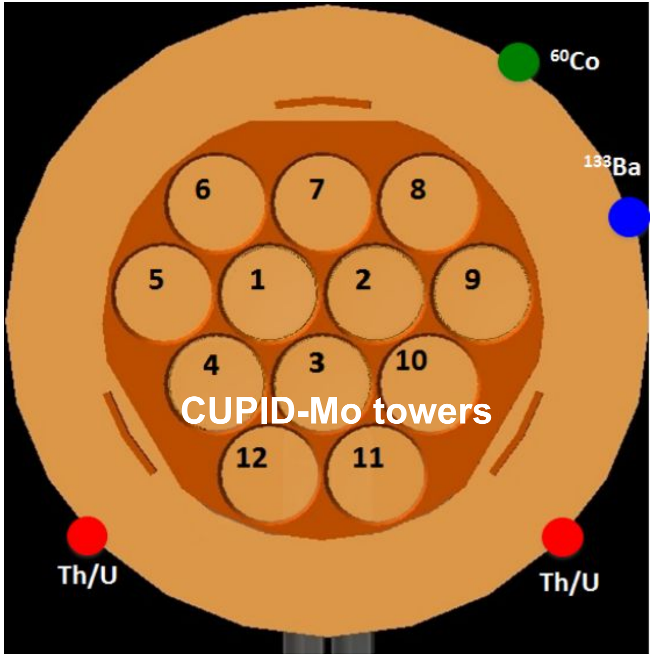
- 100 m^2 plastic scintillator **muon-veto** system
- 50 cm **PE shielding**
- 20 cm **lead shield**
  innermost 2 cm is roman lead
- **Radon free air** circulation in between lead and Cu cryostat
- Inversed geometry **wet dilution refrigerator with GM cryocoolers** for 100K screen and He liquefier
- **10 days between LHe refill**
- **In-house front end electronics** (Grenoble, CEA-Saclay)

CUPID-Mo at Modane

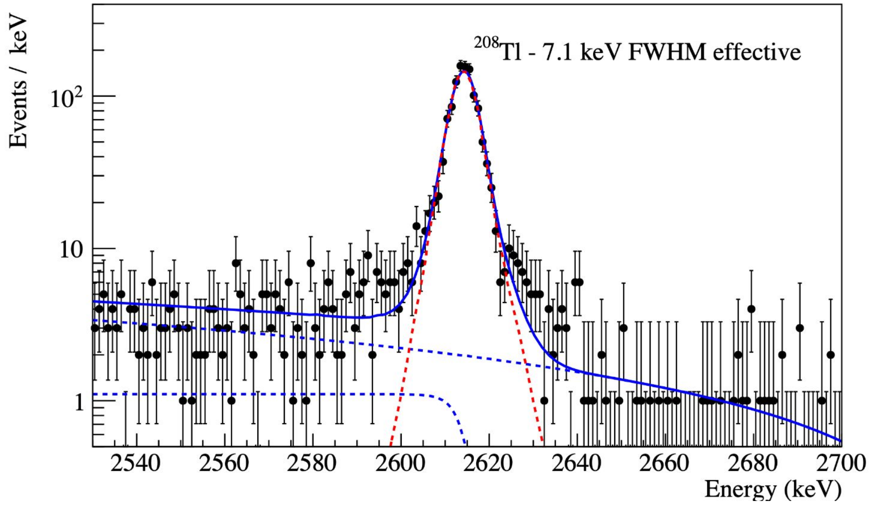
Suspension system

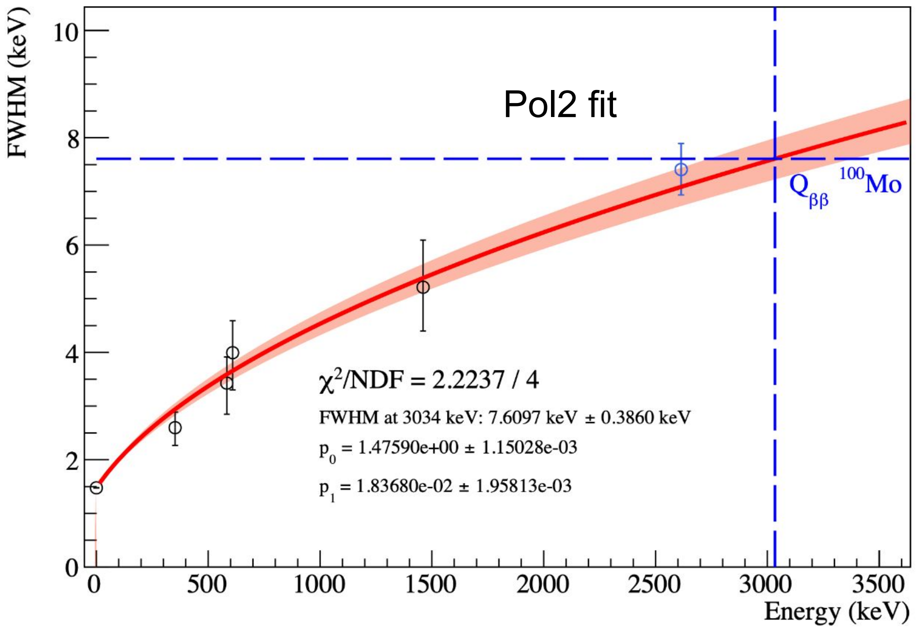


Calibration source position



CUPID-Mo energy resolution





Simultaneous unbinned extended maximum likelihood (UEML) fit to extract the (Ch,DS) - based resolutions

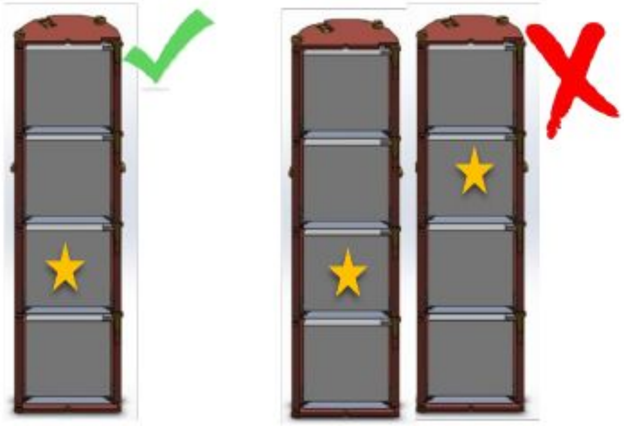
Fit model: smeared step function (multi-compton)+Gauss (photopeak)+Linear (multi-photon + 2νββ)

scaling factor from calibration data at 2615 keV applied to physics data at 3034 keV

CUPID-Mo cuts

Quality cuts

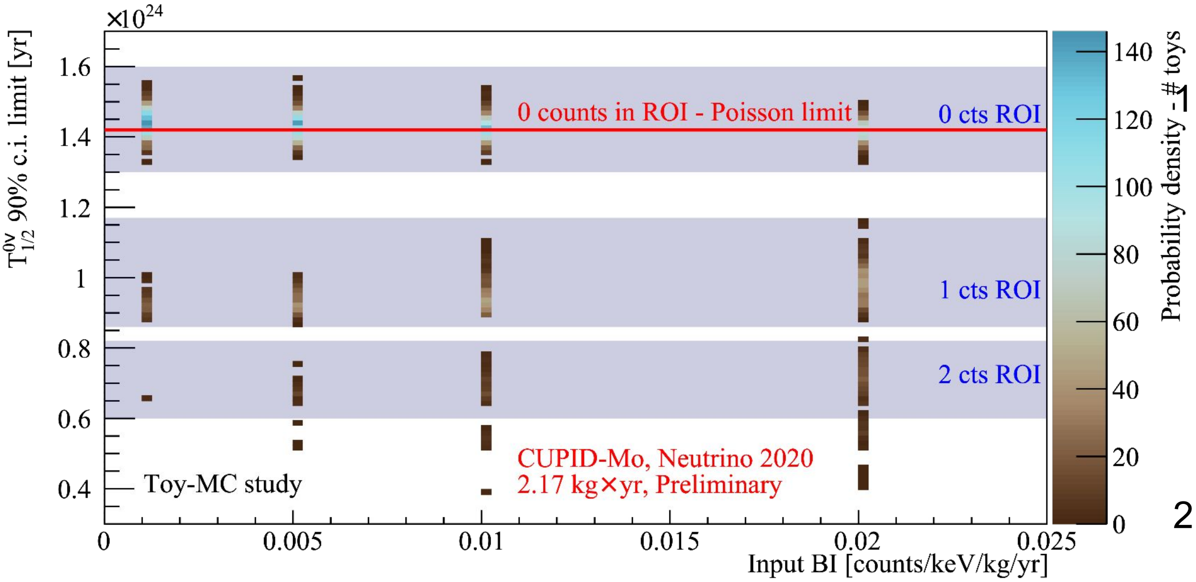
- No energy dependence
- Single trigger in 3 s pulse window
- flat pulse pre-trace (baseline slope)
- Single crystal events (M1)



Pulse Shape analysis PCA

- The LD-based cuts are independent from the event topology in the LMO crystals
- Principal component analysis
  - trained on 1-2 MeV of physics data
  - the 1st component contains the shape of a *good pulse* similar to the avg. pulse
- Define the reconstruction error as pulse shape variable

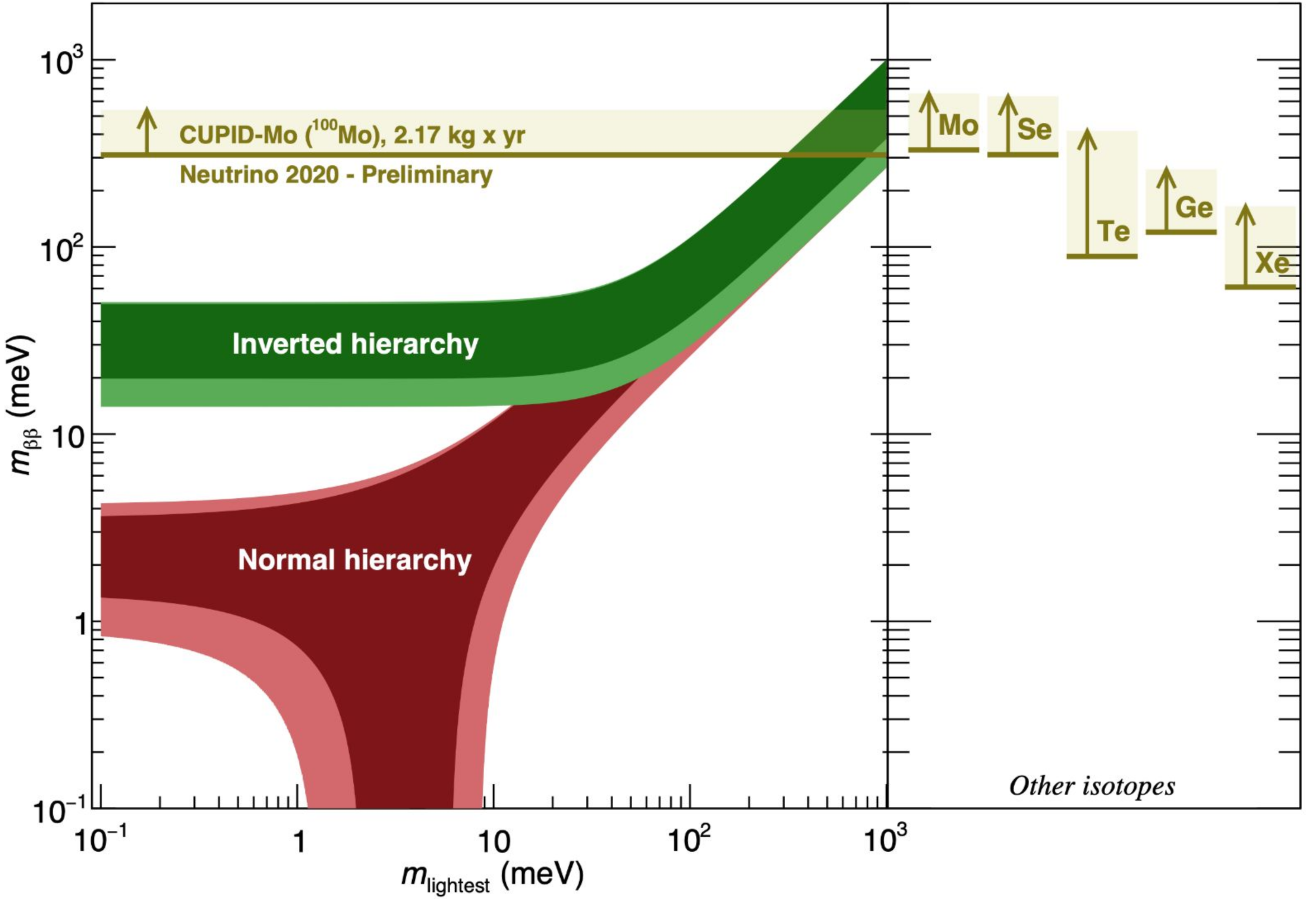
CUPID-Mo limit setting



Toy analysis was performed

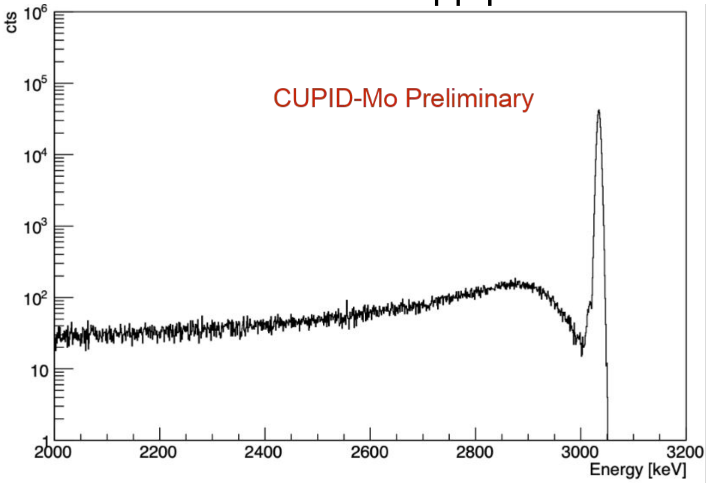
1. **Bayesian counting analysis**:
   - central bin/ROI: 75% signal and bkg
   - side band: 1% signal and bkg
   - bkg fit: exponential + linear
   - use Gaussian priors on exponential from fit in [2615-2980] keV
2. **Poisson counting analysis** as a cross-check

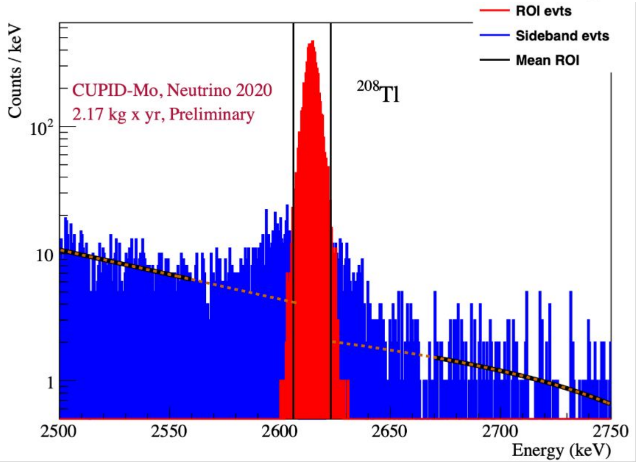
CUPID-Mo limit setting



CUPID-Mo systematics

MC simulation of $0\nu\beta\beta$ peak

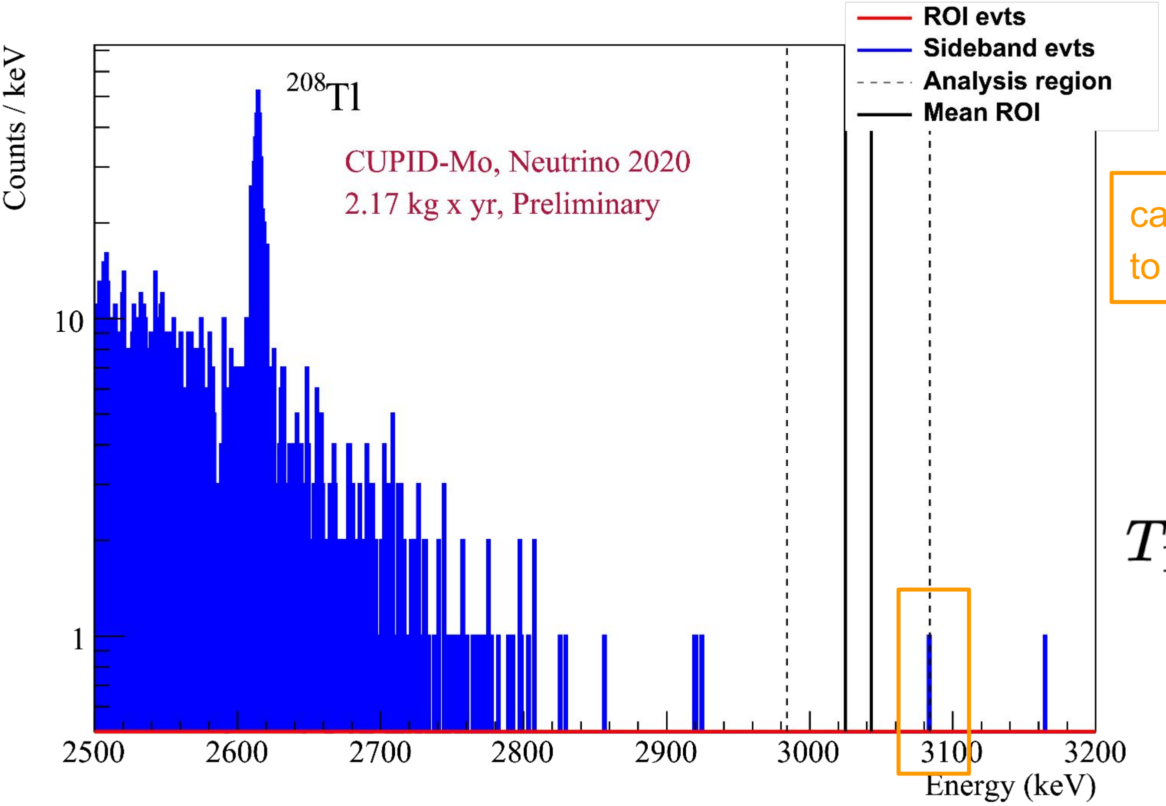




- Isotopic enrichment 0.966 ± 0.002 (gaussian prior)
- $0\nu\beta\beta$ containment MC (gaussian prior)
  - Geant4 modeling and density uncertainty (1.5%)
- $0\nu\beta\beta$ containment detector response (flat prior)
  - potential non-gaussianity of the $0\nu\beta\beta$ peak (5%)
- Analysis efficiency (gaussian prior)
  - all cuts stat. and PCA extrapolation (gaussian prior)

$$\epsilon = (90.5 \pm 0.4\ (\mathrm{stat.})\ ^{+0.9}_{-0.2}\ (\mathrm{syst.}))\,\%$$

The new 0νββ decay CUPID-Mo limit



can be rejected by delayed coincidence cut to reject pairs of ^{212}Bi-^{208}Tl

New limit

$$T_{1/2} < 1.5 \times 10^{24} yr, 90\% \; C.I.$$

CUPID-Mo background index

- Perform unbinned extended maximum likelihood fit on Bkg data excluding [3010, 3060] keV
- Phenomenological Bg model:

Exponential + Flat component